

Interference Effects Observed through Photoemission Experiments

The pressure on the magnetic data storage industry to pack more information into smaller volumes has pushed the study of thin magnetic films to the quantum level. Investigations into the properties of magnetic materials at the nanostructure scale have revealed that, when two layers of ferromagnetic material are separated by a thin nonmagnetic spacer, the relative spin directions of the ferromagnetic layers oscillate as a function of the spacer thickness. Pioneering photoemission experiments at other facilities have shown that this oscillation is associated with quantum well state effects in the spacer. New work at the ALS has revealed additional, more subtle interference effects.

According to the quantum well states model, when the thickness of the spacer is reduced to a few nanometers, the continuum of electron states normally available becomes quantized into discrete energy levels. The only energies

allowed correspond to those in which an integral number of half-wavelengths of the electron's wave function fit into the quantum well of the spacer. As the width of the well (i.e., the spacer) increases, the allowed energy levels in the spacer quantum well will shift. Whenever a quantum well level passes through the Fermi level, the energy of the system is at a maximum. To lower the system energy, the spins in one of the ferromagnet layers realign to lie antiparallel to the other layer. Therefore, the coupling between the two ferromagnets oscillates as the spacer thickness increases or decreases.

Changes in the thickness of layers other than the spacer would also affect the coupling strength of the two ferromagnets, because the electron waves reflected from all the layer boundaries interfere with the quantum well states in the spacer. Thus, changing the thickness of the ferromagnetic layer changes

the quantum well states in the spacer, which in turn determine the coupling strength. Although quantum well states in the spacer can be detected as peaks in photoemission intensity, detecting interference effects, which are easily overwhelmed by thickness variations, requires a series of highly sensitive measurements with very small thickness increments.

The ALS team overcame these difficulties and confirmed the existence of quantum interference in the spacer through an elegant experiment made possible by the small spot size of the ALS beam. Dispensing with the top ferromagnetic layer to access the information in the spacer, the researchers grew a thin wedge of copper (spacer) on top of a thin wedge of cobalt (ferromagnet) on a substrate of nickel. The wedges were layered at right angles to each other, so that their thicknesses could be varied independently by changing the direction

of the scan. The thicknesses of the layers vary by a negligible amount across the beam spot. The resulting photoemission patterns clearly show the periodic modulation of the copper quantum well states as a function of both the copper thickness and the cobalt thickness.

Not only does this work provide additional confirmation of the quantum well states model, it opens the door to future "wave-function engineering"—the manipulation and design of wave functions as needed for nanometer-size magnetic components. The researchers, led by Z.Q. Qiu of the University of California, Berkeley, are currently extending their investigations into looking at the behavior of coupled quantum wells, obtaining simultaneous images of electronic and magnetic effects, and developing a method for directly probing wave functions.

Z.Q. Qiu (510-642-2959), Department of Physics, University of California, Berkeley, and Materials Sciences Division, E.O. Lawrence Berkeley National Laboratory.

R.K. Kawakami, E. Rotenberg, E.J. Escorcia-Aparicio, H.J. Choi, T. R. Cummins, J.G. Tobin, N.V. Smith, and Z.Q. Qiu, "Observation of the Quantum Well Interference in Magnetic Nanostructures by Photoemission," *Phys. Rev. Lett.* **80** (1998) 1754.



QUANTUM WELL STATES IN MAGNETIC MULTILAYERS



Interference Effects Observed through Photoemission Experiments

- In the 1980s, artificial nanostructures revolutionized semiconductor physics and applications
- Now, a similar revolution is occurring with respect to thin magnetic multilayers, leading to
 - *Applications to storage technologies*
 - *Customized magnetic materials*
 - *Exploration of the fundamental physics of magnetism*
- This work
 - *Systematically studies quantum well states (QWS) in multilayer films*
 - *Directly probes the quantum well wave function*
 - *Opens the door to future “wave-function engineering”*



QUANTUM WELL STATES IN MAGNETIC MULTILAYERS

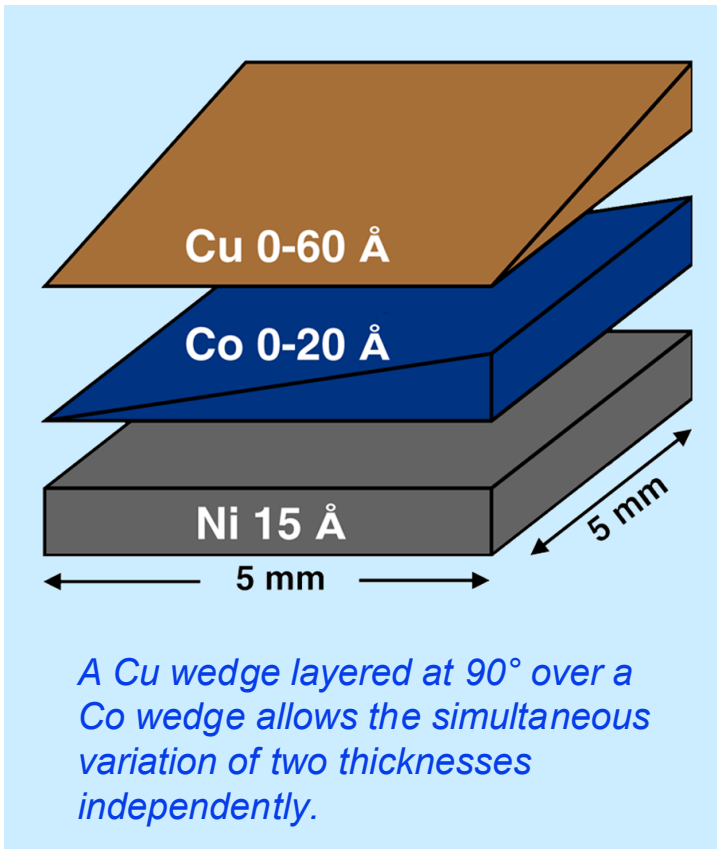


Interference Effects Observed through Photoemission Experiments

- **Thin magnetic multilayers have been well studied**
 - *Nanometer-scale layers act as 1-D quantum wells*
 - *Existence of QWS in layers established by pioneering photoemission experiments conducted elsewhere*
- **ALS photoemission techniques reveal more subtle effects**
 - *Interference between QWS in different layers*
 - *Effect is dependent on layer thicknesses*
 - *Observation requires a series of photoemission measurements in which layers vary in thickness*
 - *Use of wedged samples can accomplish this in a single scan*
 - *Only possible with small spot size of ALS beam: negligible variation in wedge thickness across beam spot*

QUANTUM WELL STATES IN MAGNETIC MULTILAYERS

Interference Effects Observed through Photoemission Experiments



Photoemission as a function of both Cu and Co thicknesses shows interference between QWS in the two layers.

